Hybrid RF / Optical Communication Terminal with Spherical Primary Optics for Optical Reception

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Abstract - **Future deep space communications are likely to employ not only the existing RF uplink and downlink, but also a high capacity optical downlink. The Jet Propulsion Laboratory (JPL) is currently investigating the benefits of a ground based hybrid RF and deep space optical terminal based on limited modification of existing 34 meter antenna designs. The ideal design would include as large an optical aperture as technically practical and cost effective, cause minimal impact to RF performance, and remain cost effective even when compared to a separate optical terminal of comparable size. Numerous trades and architectures have been considered, including shared RF and optical apertures having aspheric optics and means to separate RF and optical signals, plus, partitioned apertures in which various zones of the primary are dedicated to optical reception. A design based on the latter is emphasized in this paper, employing spherical primary optics and a new version of a "clamshell" corrector that is optimized to fit within the limited space between the antenna sub-reflector and the existing apex structure that supports the sub-reflector. The mechanical design of the hybrid accommodates multiple spherical primary mirror panels in the central 11 meters of the antenna, and integrates the clamshell corrector and optical receiver modules with antenna hardware using existing attach points to the maximum extent practical. When an optical collection area is implemented on a new antenna, it is possible to design the antenna structure to accommodate the additional weight of optical mirrors providing an equivalent aperture of several meters diameter. The focus of our near term effort is to use optics with the 34 meter DSS-13 antenna at Goldstone to demonstrate spatial optical acquisition and tracking capability using an optical system that is temporarily integrated into the antenna.**

I. Introduction

The first phase of the hybrid RF/optical terminal design task consisted of a broad based trade study considering shared aperture versus partitioned aperture approaches, prime focus versus Cassegrain designs, various RF/optical separation techniques, and many other design factors. Some of the challenges faced when considering the hybrid terminal problem are discussed in our May 2010 IPN Progress Report [1]. A key requirement imposed in the study was that the addition of optical capability shall have minimal impact on the world-class performance of the RF ground station at 7.2, 8.5, and 32 GHz. All high level trades limited the present study to a ground terminal that could be integrated on the present DSN 34 meter beam waveguide antenna platform and demonstrated at DSS-13, a 34 meter beam-waveguide (BWG) antenna at the Goldstone Deep Space Communications Complex in southern California.

At the conclusion of phase one, two designs were put forward for further study. The designs were chosen, in part, because they differed in almost every aspect of the design space. The first design is a polished metal panel approach, discussed in a previous paper [2]. It employs a shared aperture where both the RF and optical signals share a portion of the primary. The primary surface is made up of high quality polished aluminum panels that are compatible with high efficiency RF operation and moderate spot size performance in the optical (1.5 μm) regime. This system is in general incompatible with existing small optical detectors but can, in principle, have similar performance under some circumstances if enough optical collection area is provided. The system suffers from decreased performance when the link must operate at small Sun-Earth-Probe (SEP) angles that generally occur at low data rate regimes in the overall mission space. Finally, in this system, the separation of the RF and optical signals is envisioned to occur at the Cassegrain focus.

The second design to emerge from the trade study is covered below. This second design is based upon a more conservative approach and employs relatively high quality glass or ceramic optics, and is compatible with existing optical communication detector technology. Smaller spot sizes provided by

higher quality optics allow a substantial reduction in the required optical aperture with respect to the polished panel approach described above. In the present design, a partitioned aperture is used to simplify a demo and control cost, with RF/optical separation occurring at the secondary surface. In the following sections we will describe this second design in more detail, discussing the primary surface, nested clamshell corrector, RF/optical separation, preliminary mechanical aspects, and RF design features. Finally, conclusions are drawn and future plans are discussed.

II. Overall Concept

The present approach uses numerous spherical optical mirror panels in the central 11 meters of the antenna, combined with a "clamshell" type spherical aberration corrector (SAC) that is located behind the central part of the sub-reflector. This clamshell SAC is small enough to fit in the existing area between the sub-reflector and the apex structure above it.
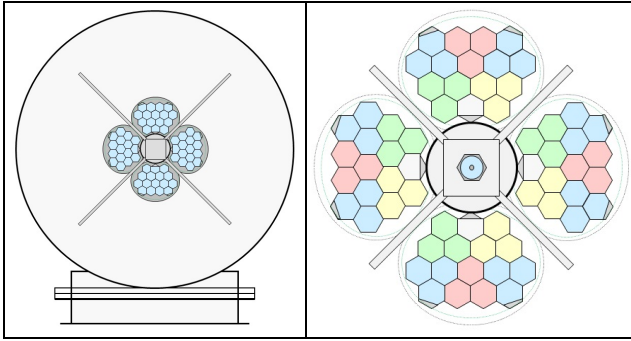

Figure 1. Front view of hybrid antenna and optical receiver, with detail of optical primary mirror area at right. This design has an optical area equivalent to 8.3m of unobstructed circular aperture. The small object at center is the clamshell Spherical Aberration Corrector (SAC), shown to scale.

The primary mirror segments are clustered into four large groups (3 groups if antenna has tripod), with each group having a sub-structure that may be tilted and moved in the Z-axis to compensate for large variations (droop) in the antenna structure that occur at different elevation angles, temperatures, etc. Figure 1 shows a grouped approach for hexagonal primary mirror panels. The dark area around each mirror cluster defines the minimum darkened area needed to control stray light.
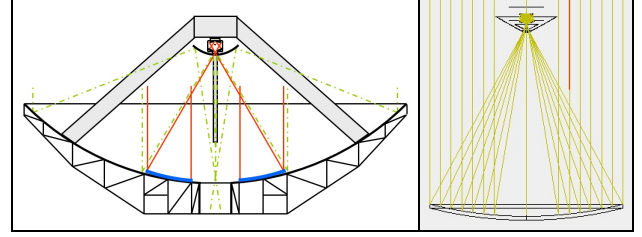

Figure 2. Side view of RF antenna primary reflector dish having optical mirrors in the central area. Optical rays are shown in solid lines and the RF is shown in phantom lines. While not shown to scale here, the clamshell SAC fits in the small area between the existing sub-reflector and the antenna apex chord structure. The right image illustrates the optical aspect only, with the exception of showing the RF sub-reflector that surrounds the SAC. The clamshell SAC, here shown to scale behind the antenna sub-reflector, is the small feature just above where the optical rays from the primary converge.

For the present study we consider only cost-effective approaches that are compatible with the current 34m beam-waveguide antenna backup structure. Thus, the focal length of surrounding RF panels ultimately drives the maximum optical focal length, then, capability of the clamshell SAC determines the maximum optical f/ratio. An additional consideration is the available space in which to fit a clamshell SAC, which in turn drives system performance versus primary mirror aperture. This is detailed in the section on the clamshell. Combined, all of these considerations, plus the required resolution, limit the primary mirror f/ratio to about f/1.0. This in turn limits the diameter of the optical area to roughly 10.8 meters. After accounting for sub-reflector obstruction, clearances, and the fill factor discussed above, the available optical area within this 10.8m area is equivalent to a telescope of approximately 8.3 meters aperture.

The received optical signal reflected from the primary mirror reaches the clamshell SAC via an annular region in the sub-reflector consisting of an optical element having a coating that reflects RF but transmits optical. The annular area is as small as possible in order to reduce its RF noise temperature contribution.

The existing DSS-13 antenna (Figure 3) is a 34 meter RF ground station that is currently used for experimentation. For an optical demonstration on DSS-13, it may only be possible to partially populate the primary mirror area due to weight limitations of the existing antenna structure. In a

worst case scenario, a retrofit to DSS-13 could be limited to no more than about a 4m equivalent optical aperture, which is equivalent to one mirror panel cluster. An adequate pointing and tracking demonstration could be accomplished with as few as 5 to 7 primary mirror panels and either a full clamshell SAC or one or more off-axis segments of the SAC optics. The full clamshell is preferred because it provides more freedom in location of mirror panels in a partially populated system.

Figure 3. DSS-13 antenna. Left: General view showing tripod and sub-reflector. The pedestal area is underground. Right: Detail of the sub-reflector and its supporting apex structure, showing the limited available area for a clamshell SAC.
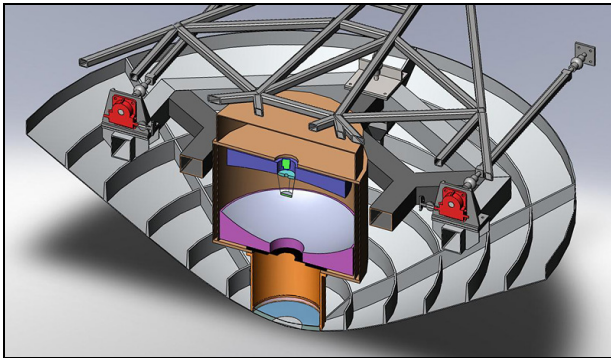

Figure 4: SolidWorks model of clamshell SAC optics, also showing the antenna sub-reflector and lower apex chord to scale. The mirror substrates, clamshell housing, and optical bench fit in the area below the apex structure. A "vertex lens" at the sub-reflector center admits the received optical signal.

III. Primary Mirror Surface

The primary mirror surface is spherical, consisting of a relatively large number of identical hexagonal or circular mirror panels. The exact panel size is still to be determined, but widths under consideration range from 60cm to 1m. The smaller 60cm width correlates to the largest amateur (or other low cost) reflecting telescope optics that were observed to tolerate prolonged direct solar illumination. The larger panel size is based on the

widest available size of suitable "low cost" mirror blank material. One meter mirrors are shown for illustrative purposes, but detailed analysis and some tests will ultimately determine the final panel size.

The primary mirror panels are clustered into four large groups (3 groups if the antenna has a tripod), each group having a sub-structure that may be both tilted and moved in the Z-axis to compensate for large changes (droop) in the antenna structure that occur according to elevation angle, temperature, and other factors. Primary mirror panel grouping is also intended to permit use of steering mirrors to independently correct moderate to high frequency pointing errors of each mirror group. Grouping also permits the primary mirrors to have clearance from areas immediately behind the sub-reflector and its supporting tripod or quadrapod. Mirror panel grouping results in a less efficient primary mirror "fill factor", but has the advantage of retiring some risk and permitting a staged demo implementation.

The individual panels within each group are also actuated, but these need only be actuated over a small angle corresponding to differential pointing error between the panels in each group. We are considering actuating groups of three mirrors, as shown in the color coding of figure 1.

Demonstrations based on the present design may show that custom built configurations could have a better fill factor. For spherical primary optics, the maximum achievable aperture width is determined largely by the maximum primary mirror f/ratio that can be adequately corrected by a clamshell SAC.
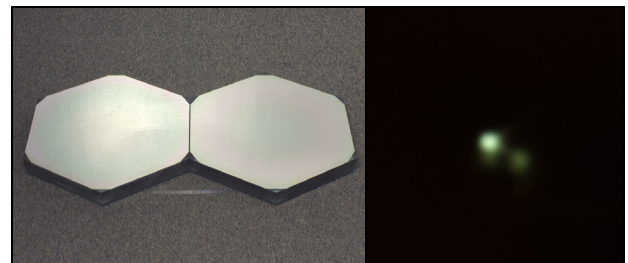

Figure 5. Left: These low cost 35 cm wide mirror elements (about half the size envisioned for an operational system) were acquired for initial testing and coating process evaluation. These prototypes have a focal length of 12 meters and a durable coating suitable for both optical and RF reflection. Right: Distant terrestrial light sources, imaged by one of the mirrors and cropped to a 1 mrad FOV. Even at the low 8 degree elevation angle (and during unfavorable atmospheric seeing

conditions) the 90 percent encircled energy spot is less than 100 µrad. Some features are light falling on distant buildings. The allowed spot size for each operational mirror will be 7 to 10 µrad, excluding atmospheric effects.

IV. Clamshell Spherical Aberration Corrector (SAC)

A clamshell SAC above the antenna sub-reflector corrects spherical aberration inherent in a segmented spherical primary mirror. This SAC is a new design that addresses requirements specific to the hybrid. Some of the requirements include that:

1. The SAC with its housing shall function under both night and day and night conditions, without the need to be manually covered and uncovered in response to weather conditions. 2. The SAC shall also adequately correct additional aberrations imposed by the "lens" which forms an annular section of the RF reflector but lets the optical signal pass through. 3. The SAC and its housing shall fit between the existing antenna sub-reflector and apex structure, to permit installation without major structural changes to the antenna, while also accommodating an optical bench on the back side or the SAC module. 4. The foregoing imposes a requirement that the SAC shall provide adequate correction even though it is located in an unconventional longitudinal position with respect to the caustic of the primary mirror. 5. The SAC shall provide an accessible focal surface location with an output f/ratio slower than f/2. The slower f/ratio output facilitates relatively efficient collimation of the received light bundle. 6. Finally, the SAC and related systems shall also minimize how much RF gets to the optical detector. The solution is a new "nested" clamshell SAC design. A specific example of the clamshell SAC design is described below.
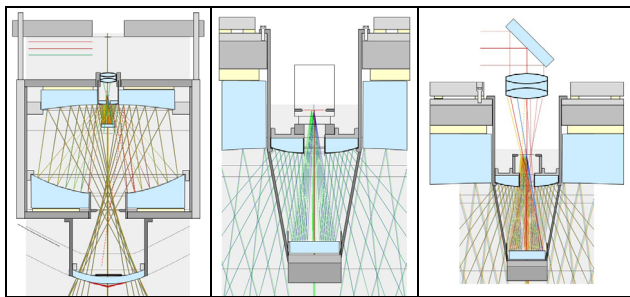

Figure 6. Details of the clamshell Spherical Aberration Corrector (SAC). The left image shows the clamshell SAC, with its smaller nested optics on the top side. A "vertex lens"

below it (covered in a later section) admits the optical signal from the primary mirror, but reflects the RF signal. The center image shows the nested optics in some detail, along with the f/3 focus that is accessible to appropriate cameras of sufficiently small physical size to fit within the 11 cm diameter recess surrounding the focal surface. The mirror at the bottom of the figure is supported by struts that fall within the "shadow" of the antenna sub-reflector support structure. The right image shows a notional relay lens and fold mirror that direct the optical path to an optical bench on the back (top in image) of the clamshell.

Figure 6 provides an overview of the clamshell SAC, along with some detail views of its smaller nested components. The illustrated rays are from our Zemax [3] model of the optical system. In addition to modeling SAC optical surfaces, we used Zemax in an unconventional way to also model the back surfaces of some mirrors and mechanical attributes of the antenna that define the available envelope in which the SAC must reside. This provided a good way to determine when the clamshell design had been "miniaturized" to an appropriate degree, which in the present case was to get the diameter of the largest mirror below 90 cm. The largest SAC mirror is only 88 cm in diameter, or about 8 percent of the 10.8 meter spherical primary mirror panel array aperture. The conics of the largest two SAC mirrors are relatively weak in comparison to a 2001 JPL clamshell design, [4], with the strongest conic in the system being dramatically weaker (-2.42 versus -3.92), though the tolerance on this conic is still relatively tight. The weaker conic of the new SAC, combined with its smaller size, radically reduce fabrication cost.

The strongly curved mirror at the upper center of the right two illustrations is used to provide a manageable f/ratio at the output of the system (f/3 versus f/0.7), and also reduces off-axis aberrations to a reasonable level. This in turn permits the system to accommodate a 600 µrad field of regard, though this entire field need not be imaged at the same time. The conic on this mirror is strong at nearly +7, but its relatively small (though not overly small) size permits it to be manufactured.

The mirror at the bottom of the right two clamshell SAC illustrations is flat, so it can be tilted at predetermined angles that are based on the antenna elevation angle and atmospheric conditions. This tilting permits internal compensation for the difference in atmospheric refraction for optical and

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RF, plus changes in the optical and RF boresights that are characteristic of different elevation angles. Since these factors are expected to comprise over half of the angular compensation required in the optical system, it reduces the angular range that must be covered by steering optics behind the clamshell SAC. Tilting the nested flat mirror also eliminates clipping of areas in light bundle that would otherwise result in the absence of radically oversized optics on the optical bench on the back side of the clamshell. We anticipate that only the central 400 µrad FOV will be needed to compensate for atmospheric refraction except during the worst 1 percent case for temperature and humidity.
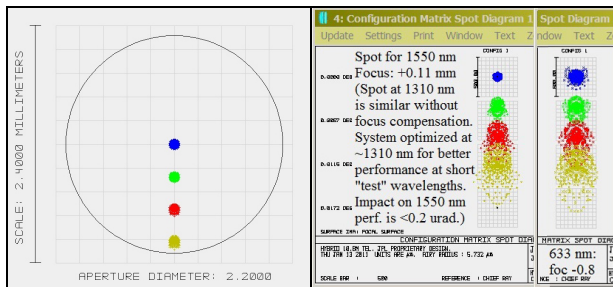

Figure 7: Left: Footprint diagram for central 60 µrad field of view (FOV) at the SAC focus. Right: Spot diagrams for 1550 nm (left column) and 633 nm (right column). Upper spots are axial. Lower spots correspond to 100 µrad steps off-axis, out to a 300 µrad radius. The physical size of the 95 percent encircled energy axial spot is just over 0.1 mm, while the spot size at the greatest off-axis distance approaches 0.5 mm and is not well centered about the chief ray. This corresponds to about 3 and 15 µrad (respectively) in angular resolution. Actual resolution is somewhat less than this after accounting for optical alignment tolerances, etc.
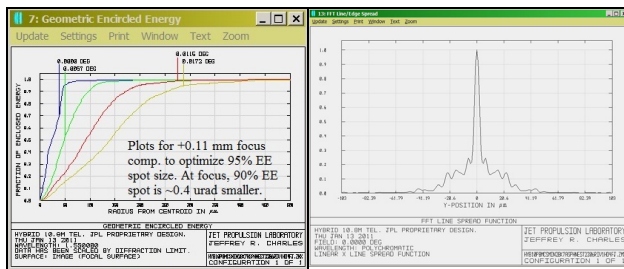

Figure 8. Encircled energy plots. Left: Geometric encircled energy plot for 1550 nm, with focus set 0.11 outside of paraxial ray focus in order to reduce the 95% encircled energy spot size in light of a fractional wavelength residual spherical aberration. The vertical grid lines each represent 50 microns radial distance from the spot center, at a focal length of 32,700 mm. Right: FFT line spread function showing that significant energy is contained in the axial spot out to almost 50 microns radius, or about 1.5 µrad in angular radius. The design is not diffraction limited, but is more than adequate for the optical communications application. The optical system will not

provide spot sizes this small in practice, due to allowed tolerances in optical figure and alignment, plus the effects of temperature and atmospheric seeing.

Component / (Designation)	Radius of Curvature	Spacing, mm	Diameter (phys. / util.)	Conic Constant
Primary Mirror	-21891	10,262.0	10,800 / 10,794	Spherical (0)
RF Separator Vertex Lens	+220.6	34.18	444.0 / 336.5	-9.150
Back Surface Vertex Lens	-199.5	1033.0	444.0 / ~300.0	-9.385 (if BK-7)
Secondary Mirror (M2)	-2006.0	516.0	780.0 / 723.6	+0.722
Tertiary 1 (M3)	-758	508.0	880.0 / 825.1	-2.41635
Tertiary 2 (M4)	+226	119.0	110.0 / 102.8	+6.920
Pointing Mirror (M5)	Infinity (Flat)	174.6 (to focus)	72.0 / 68.4	N/A (Flat)

Table 1. Prescriptions for optical element surfaces.

Combined, the end to end optical system will provide axial resolution approaching 3 µrad (90% encircled energy spot), and 6 µrad at 100 µrad off-axis, assuming perfect optical figuring and alignment. There is some contribution to the spot size from the "vertex lens" (covered below) that separates the RF and optical signals. In operation, we envision that allowed figuring and alignment errors will result in actual angular spot sizes that range from 10 to 25 µrad or slightly more. The contribution of atmospheric seeing is then convolved with this to provide an even larger "real world" spot size, with the goal being to contain the spot and tracking errors within a communication detector field of view that does not exceed 50 µrad [5].

V. RF/Optical Separation

Characteristics of spherical aberration from the primary mirrors are actually utilized to advantage in minimizing the width of an annular zone on the sub-reflector through which the optical signal must pass. This narrowing of the annular optical area in turn reduces RF noise temperature contribution that results from residual RF transmission through the coating into the 300 deg. Kelvin optical system, as opposed to seeing the cold 3K sky. This RF / optical separation region will be referred to as a "vertex lens". The Vertex lens is shaped so that its outer edge substantially matches the RF figure on the inner boundary of the surrounding sub-reflector.

Since the optical area on the sub-reflector "vertex lens" is annular, it does not need to operate as the very center of the sub-reflector. Also, since the annular region of the vertex lens required for optical is quite limited, the RF reflecting part of this optical area may be sufficiently approximated by a conic. The conic is quite strong at -9, but since it is a conic, it can be manufactured and tested, though admittedly at notable cost. Figure 9 shows the optimum fit of this conic in comparison to the "ideal" RF surface. Alternate designs for this annular surface include a section of an axicon having an off-center but circular profile. The version ultimately implemented (assuming equal performance) will be determined by cost, repeatability of the optical figure in multiple units (for spares or later hybrids) and lead time.
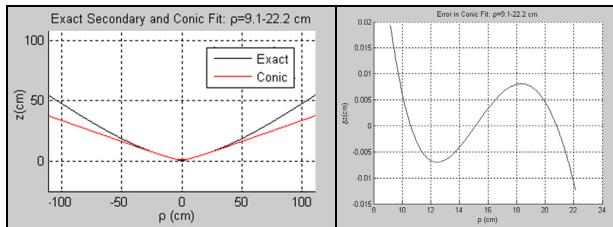

Figure 9. Comparison of the best fit of a conic to an ideal RF figure for the same zone of a sub-reflector. Left: Graphical representation of conic fit. The lines merge in the relatively small area of interest. Right: Detail plot of the small 0.1 mm maximum figure error that results from the conic fit over the optical area. The loss in RF signal strength is negligible.

Figure accuracy suitable for transmitting optical is only necessary in the central 34 cm of the 44 cm OD vertex lens. The remainder need only be accurate enough for RF reflection. Considerable margin is included on the substrate to allow for figure errors on the outer part of the strong conics. A smaller OD will be used if vendors can fabricate it without this much additional substrate size. We envision that the outer part which is not used for optical will have a thick aluminized coating that provides efficient RF reflection.

At the center of the vertex lens, inside the annular optical area, a conventional pointed vertex plate of about 190 mm diameter is used. To provide a good RF surface, the outer edge of the vertex plate is tangent with a zone about 2 mm beyond the inner part of the annular optical surface. Tangency is not right at the plate edge due to the minimum edge thickness that can be manufactured and maintained.

While it would be desirable for the vertex lens to have no effect on the optical signal, it must be of measureable thickness to facilitate fabrication. In spite of this, the vertex lens is designed to impose only modest changes in the optical spot size at different wavelengths, which in turn permits testing and pointing validation at wavelengths shorter than the envisioned 1550 nm optical comm wavelength.

To provide compatibility with the widest range of test and communication wavelengths, while also emphasizing good performance at 1550 nm, the back surface of the vertex lens is optimized so the system provides the smallest spot (just over 2 µrad) at 1310 nm wavelength. If perfect optical alignment is assumed, this provides axial spot sizes of just over 3 µrad at both 1064 nm and 1550 nm, and a 5 µrad spot at 633 nm. Slight shifts in focus (<1 mm) are required to get the best spot size versus wavelength. This is sufficient performance, though if necessary, it would be possible to provide more correction for spot size versus wavelength in the aft optics on the optical bench behind the clamshell.

Tests of RF/optical separator samples to date indicate that when the RF reflection efficiency is about 90 percent, the optical transmission at 1550 nm is only about 89 percent. [1] This is obviously an area that could benefit from some improvement.
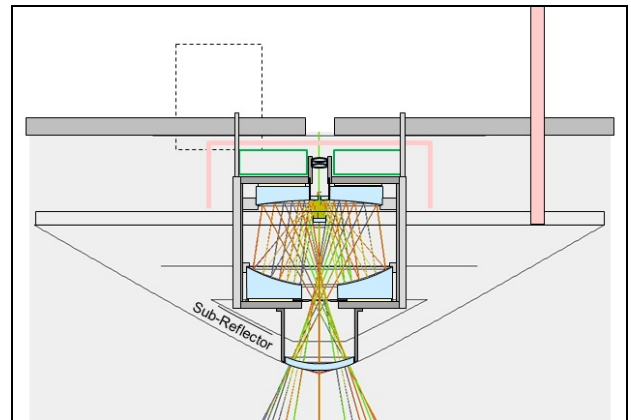

Figure 10. Optical RF separation at the surface of the sub-reflector is accomplished via appropriate coatings on an aspheric meniscus lens. This simplified cross section shows of the RF sub-reflector and meniscus lens (bottom center) in association with the optical clamshell SAC. The optical signal passes through an annular region of the meniscus lens. The dashed rectangle toward upper left represents the envelope of a cryogenic detector dewar, that, if used, would barely fit between members of the antenna apex chord.
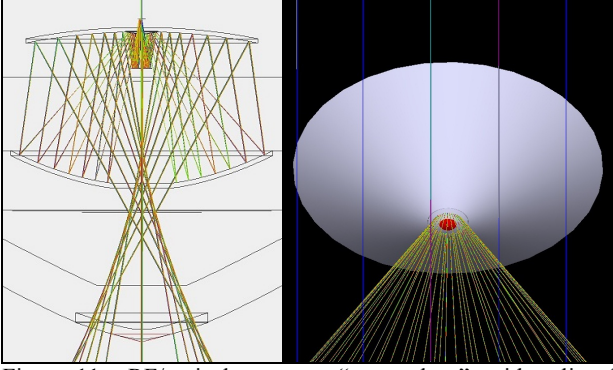
Figure 11. RF/optical separator "vertex lens", with a literal vertex plate at center. Left: Zemax screen shot of optical rays from primary mirror passing through the RF/optical separator "vertex lens" at bottom and ultimately arriving at focus at the top of the SAC. Right: In this view looking up at an oblique angle toward the sub-reflector, the red spot at center defines a 19 cm diameter area that is occupied by a metal vertex plate. This central area is not utilized for optical. The faint circle surrounding the optical rays defines the OD of the vertex lens.

VI. RF Aspects of the Design

The large antennas of the Deep Space Network employ a dual-shaped design, where neither the primary nor the secondary is a conic section. Rather, these surfaces are numerically generated to transform the tapered illumination from the RF feed at the secondary focus into phase coherent uniform illumination of the primary, which provides the maximum gain available from the aperture antenna. Currently the secondary is shaped in a manner to provide no illumination over the 2.4 meter diameter beam waveguide exit aperture in the center of the primary. This maximizes the power available for distribution over the remainder of the surface. In the hybrid RF/optical design the secondary is reshaped to provide no illumination over the entire 10.8 m diameter optical surface. In this particular case the area loss maps to a loss of approximately 0.46 dB in the RF communication link.

The second figure of merit for the RF communication link is the system noise temperature. For a typical Deep Space Network system the noise temperature is extraordinarily small, as low as 26K for an 8.5 GHz downlink system. In addition to the low noise amplifier contribution, this system noise temperature includes spillover in the beam-waveguide system, scattering by the secondary support struts, spillover past the primary and a number of other sources. In general,

any stray path from the RF feed to room temperature objects such as the ground, beam waveguide shroud, etc. will add noise. For the hybrid system discussed here, the primary source of excess noise is leakage through the RF/optical splitter coating into the room temperature optical system. We may compute the total leakage by taking into account the feed horn's radiation pattern at the secondary, the coating leakage of approximately 10%, and the physical temperature of the optical system, 290K. Taking all these factors into account the computed leakage is approximately 0.3%, resulting in a noise source of slightly less than 1K. For a nominal system temperature of 26K the additional noise results in a loss in link performance of 0.16 dB.

Of course, the overall trade-space allows for enhanced RF performance at the expense of optical performance. Examples include the use of less optical collection area, or a change in the prescription of the RF/optical coating which would decrease the RF leakage at the expense of optical transmission and thus reduce the noise contribution of the splitter. Design of a final fielded system would consider the relative cost/benefit obtained by increasing the overall RF reflector diameter to compensate for the loss in RF link performance due to the addition of the optical system.

VII. Optical Communications Detector/Equipment

The optical aspect of the hybrid RF / optical terminal is designed to be compatible with multiple optical communication detector approaches. Communication detector assumptions include approaches that are the most stringent in terms of the maximum permitted angular field of view on the daytime sky, and that are also being seriously considered for optical communication operations by parties outside our immediate task. The more stringent requirements are that the angular field of view of the communication detector shall not exceed 50 µrad.

This obviously imposes the requirement that the optical spot size shall be smaller than the detector field of view, in order to allow for tracking error and atmospheric scintillation (seeing) effects, etc.

Some optical communication detectors require cryogenic cooling, while others do not. The system is obviously easier to implement in the absence of cryogenic cooling, but we are proceeding based on anticipating that cryogenic cooling of a detector may be required. Related considerations include reducing the coolant line length and accommodating the additional dimensional envelope needed for a cryogenic detector head.

VIII. Mechanical Aspects of the Design

To implement optical without changing basic or significant aspects of the 34 meter antenna design, mechanical aspects of the existing antenna design drive some aspects of the optical configuration.

Therefore, attributes such as the articulated primary mirror support structure must be implemented (at least in a retrofit) in a way that does not interfere with the existing but necessary structural members of the antenna primary. The maximum primary focal length (and thus the greatest optical area) may be realized by locating only the front members of the optical primary mirror sub-structure in front of the antenna primary reflector structure, then running the aft members of the optical sub-structure between existing structural members in the antenna.

For maximum flexibility, the primary mirror panels are separated into large groups, with the active area of each group being limited to areas that are not shadowed by the antenna sub-reflector or associated support members. Each mirror group has a sub-structure that attaches to the antenna at only three locations. Once each spherical primary mirror group and its sub-structure is installed, it need only be moved in the z-axis at the attach point nearest the center of the antenna, and tilted via actuators on the outer two attach points. Translation is not necessary, since z-axis plus tilt are the only degrees of freedom needed for spherical optics.

Thickness of the optical mirrors and their associated floatation and forward sub-structure members may require that the optical mirror surface be about 15 cm in front of where the RF reflector surface would otherwise be located, at least in a retrofit. This situation could be modified in a new build. To simplify some aspects of maintenance or eventual de-commissioning, aft members of the sub-structure

may be bolted, aligned, and tack welded, as opposed to using full welds. This is obviously an area for further study.

To install the clamshell SAC with minimal impact on the antenna, the most significant modification involves the hexagonal interface between the sub-reflector and the apex structure. This hexagonal member would be replaced by one having the same interface to the sub-reflector, but that has a hole in the center large enough to accommodate the clamshell SAC. Some actuators on the hexagonal structure that interface with the apex structure would have to be relocated, but we have arrived at several workable configurations for this.

Optical analysis has shown that there is little benefit to independent actuation of the clamshell with respect to the sub-reflector (owing to the required critical alignment between the clamshell and vertex lens), so our current baseline approach is to hard mount the clamshell and vertex lens assembly to the combined modified hexagonal structure and sub-reflector. Proper registration of the vertex lens RF surface to the surrounding sub-reflector determines the alignment. Actuation of the primary mirror groups then compensates for relative motion of the clamshell. Hard mounting the clamshell to the sub-reflector interface also permits more height for the clamshell and optical bench, since the area that would have been allocated to clamshell motion can instead be allocated to its envelope.

IX. Conclusions and Future Plans

The overall viability of the hybrid terminal approach includes not only optical and RF performance, but also encompasses the cost and operational complexity relative to separate RF antenna and optical assets. This study does not undertake to address selection of ideal sites, but instead starts with the assumption that a prototype hybrid RF/optical asset will, if implemented, be demonstrated at Goldstone.

Future studies and demonstrations will focus on retiring risks associated with a hybrid approach, including risks unique to the most demanding aspects of operation. Accordingly, a great deal of effort will be directed toward achieving optical performance adequate for both day and night

operations, with what is essentially an "outdoor" optical system.

In the coming months and years, we propose to accomplish the following:

a.) Implement and demonstrate optics and control systems sufficient to achieve optical spot sizes of 20 to 32 µrad with the end to end optical system, including optical alignment errors, optical figure errors, mechanical or temperature induced optical figure changes. This spot size does not include atmospheric effects. To demonstrate viability as a reliable optical asset, this performance must be maintained even during the day. A goal is for a new operational system to perform slightly better.

b.) Co-align optics and an imaging system with the antenna electrical boresight and characterize differential pointing of mirror panels while also accumulating data for optical pointing versus the antenna electrical boresight, and antenna pointing control. Initial tests will not require large optics.

c.) Develop and demonstrate a cost effective yet functional and relatively low maintenance mirror "outdoor" panel actuator and control system. This includes an appropriate degree of mirror grouping.

d.) Implement and demonstrate the clamshell SAC in conjunction with a partially populated primary mirror, then gradually fully populate the primary.

e.) Demonstrate acquisition of stars and planets with optics on the antenna during both day and night conditions, including at relatively small angles from the sun.

f.) Evaluate and test impact of nearly focused solar image falling on sub-reflector at near sun angles.

g.) Implement and test ancillary pointing and tracking systems, including tilting of the flat mirror in the clamshell SAC and steering mirrors in an optical bench that is on or in proximity to the SAC.

Emphasis of tilting flat mirror in clamshell is to take out the difference in atmospheric refraction between RF and optical while also minimizing vignetting that would occur if implemented aft of the SAC. From this, a lookup table would be developed and refined to provide an offset angle that is based on elevation angle, humidity, and ambient temperature, etc.

h.) Conduct partial aperture optical communication experiments with a near field optical terminal, followed by full aperture demonstrations with more distant terminals (airborne, for example), then ultimately perform communication demonstrations with a space based terminals, eventually followed by actual operations.

Acknowledgement

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